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Bradley, Stuart ; Mikkelsen, Torben

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A REVIEW OF SODAR ACCURACY

Stuart Bradley¹, Torben Mikkelsen²

¹*Physics Department, University of Auckland, Private Bag 92019, Auckland, New Zealand,
s.bradley@auckland.ac.nz*

²*Department of Wind Energy, Risø Campus Frederiksborgvej 399, 4000 Roskilde, Denmark, tomi@dtu.dk*

ABSTRACT

What accuracy and reliability can today be expected from SODAR wind measurements? Is there traceable evidence for performance? Environmental factors, turbulent fluctuations and non-uniform terrain all affect the wind speed uncertainty. So site-to-site variations for SODAR-mast comparisons can be large. On a uniform terrain site, differences between a SODAR and a mast-mounted cup anemometer will arise due to turbulent fluctuations and wind components being measured in different spaces, as well as to variable background noise. We develop theories for turbulence-related random fluctuations due to finite sampling rates and to sampling from spatially distributed volumes. Effects can be minimized by selecting the environment and selectively filtering the data for periods of low fluctuations. But there is still real difficulty in answering the question: How good is a SODAR? Most field use, away from an idealized test environment, appears to produce SODAR-mast rms differences greater than the 0.1 m s⁻¹ or less typically quoted by SODAR manufacturers. However, in these real environments it is likely that much of the difference arises from the mast sensors and the SODAR actually measuring in different spaces. We show some field results which reinforce this view. Both the turbulence-related random fluctuations and systematic errors in complex terrain (where systematic wind shears arise) can potentially be removed by use of a vertical column geometry. Field results from a new bistatic receiver shed some light on the differences between such ‘common volume’ sampling and the usual monostatic sampling.

1. INTRODUCTION

A FP6 EU Program, WISE, reported in 2004 on the state of the art at that time for the use of SODARs in wind energy applications [1]. The conclusions were broadly that SODARs provided a number of advantages compared with mast installations but were not a direct replacement because of significant differences in estimated wind speeds. It was recommended that a small mast installation be used alongside a SODAR. A successor EU program, UpWind, researched improvements in remote sensing, particularly wind energy LIDARs which had emerged toward the end of WISE. Considerable effort in UpWind has gone into

mast-LIDAR intercomparisons, with the result that, with careful field setup and data filtering, remarkable correlations can be consistently obtained between LIDAR winds and mast installation winds. Nevertheless, the final project report still recommends use of an accompanying small mast [2].

What do the reported R^2 values mean in terms of predicting differences in measured wind speed? What quality of wind measurements can be expected from SODARs in a typical installation? The first question arises since these differences between cup anemometers and remote sensing instruments are the essence of whether remote sensing gives ‘bankable’ data. The second question is relevant since the push during UpWind has been to perform intercomparisons under very restricted and controlled conditions, quite unlike those typically encountered at wind farm sites.

2. CORRELATION BETWEEN MAST AND REMOTE INSTRUMENTS

The quality of remote sensing instruments is generally judged by performing an intercomparison experiment such as PIE [3]. In an intercomparison wind speed and direction are measured at several heights by cup anemometers (and/or sonic anemometers) on a mast together with measurements by a remote sensing instrument where a number of sampling volumes are centered on the same heights as the mast measurements. For simplicity in the following we describe the geometry in (x, y, z) coordinates where the mean wind U is in the $+x$ direction, the remote instrument is co-located with the mast, and variations in wind vector components are (u, v, w) . A scatter plot is obtained from N measurements of mast instrument wind speed $U_{m,n}$ and the corresponding remote instrument wind speed $U_{r,n}$ where $n = 1, 2, \dots, N$. Similar pairs of measurements are made of wind direction, but for simplicity we will concentrate on wind speed. Neither of the measurement pairs, $U_{m,n}$ and $U_{r,n}$, necessarily is equal to the actual wind, U_n , which includes the turbulent fluctuations, because all instruments exhibit measurement errors. However, it has been conventional to consider the mast measurements as error-free and to attribute any error or differences as coming from the remote measurements. So we can write

$$U_{r,n} = U_n + \varepsilon_{r,n} \quad (1)$$

Any systematic bias in differences between remote and mast measurements can be tested by fitting a model to the $(U_{r,n}, U_{m,n})$ data set. Since both mast and remote instruments have been proven to be highly linear, and both give an estimated zero wind when the actual wind speed is zero, the physically sensible model to use is a straight line through the origin, of the form

$$\hat{U}_{r,n} = aU_{m,n} \quad (2)$$

This describes the best estimate, $\hat{U}_{r,n}$, for what the remote measurement will be, if a measurement $U_{m,n}$ is made at the mast. A measure of the scatter around the best fit line is R^2 , defined by

$$R^2 = 1 - \frac{\sum_{n=1}^N (U_{r,n} - aU_{m,n})^2}{\sum_{n=1}^N (U_{r,n} - \bar{U}_{r,n})^2} \approx 1 - \frac{\left(\frac{\Delta U_{rms}}{\bar{U}}\right)^2}{\left(\frac{\sigma_U}{\bar{U}}\right)^2} \quad (3)$$

since a is very close to 1. An R^2 value closer to 1 means that the differences between the two sensors are smaller. Here \bar{U} and σ_U^2 are the mean and variance of the wind speed over the measurement intercomparison, and ΔU_{rms} is the rms difference between mast measured and remote measured wind speed

$$\Delta U_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^N \varepsilon_{r,n}^2} \quad (4)$$

If \bar{U} and σ_U^2 are expressed in terms of the Weibull distribution for the intercomparison site and period, then the ratio σ_U/\bar{U} depends only on the shape parameter, k . The rms difference can arise from a number of causes, including

- The difference between scalar (cup-type) and vector (remote-type) measurements
- Remote sensing sampling over spatially distributed volumes
- Remote sensing sampling for each wind estimate spread over time
- Spatial separation between the remote sensing volumes and the mast sensor
- Remote sensing in the presence of background noise.

Except in the case of complex terrain, these differences are essentially random instead of systematic and, except for background noise, the differences are due to turbulent fluctuations in wind speed being sensed differently by the mast sensors and the remote sensors. We will treat the complex terrain case later, but concentrate for now on the random differences. Clearly, R^2 is *not* a property of the remote sensing instrument

alone. It depends on the wind regime in which the intercomparisons were completed. For example, if the wind speeds were well spread, then R^2 will be closer to 1, meaning that an R^2 value achieved at a particular site during one measurement period will not necessarily be achieved at the same site in a different measurement period. Furthermore, a larger turbulent intensity will give a larger ΔU_{rms} .

Ultimately, if the site is uniform, turbulence intensity is very low, background noise is minimal, and wind speeds are widely distributed, then a very high R^2 should be achieved by any good quality SODAR or LIDAR remote sensing instrument, since the inherent limitations of the instrument are being reached. This essentially explains why it is possible to get very high R^2 values in some intercomparisons, while much lower values are obtained in others. One of the features of the efforts in UpWind to demonstrate the quality of remote sensing of LIDAR, has been filtering the wind data to remove occasions when there are background influences such as fog, or low ratios of signal to noise (SNR), and when there is not low shear and low turbulence. The outstanding results obtained for LIDARs in UpWind show that these remote sensing instruments can approach very closely to the wind speeds measured by high quality cup anemometers under these ‘laboratory’ conditions. Less attention has been paid to reducing the ΔU_{rms} for SODARs, and we need to consider where this technology is at, and what the sources of contributions to ΔU_{rms} are for SODARs.

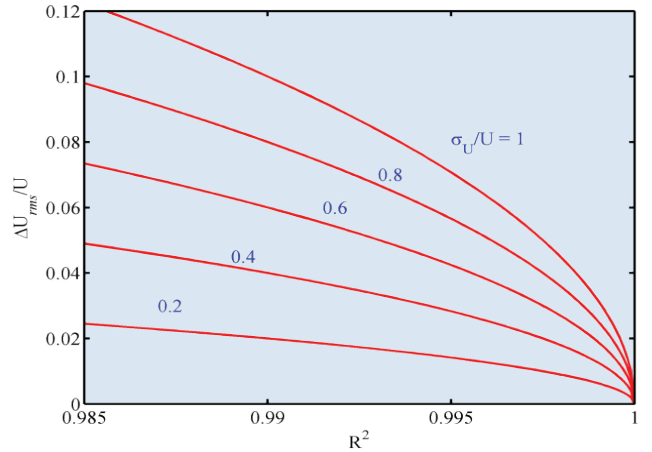


Figure 1. The relationship between fractional rms wind measurement difference and correlation R^2 .

Fig. 1 shows the relationship between ΔU_{rms} and R^2 for a range of wind regimes. For $\sigma_U/\bar{U} = 0.52$, or Weibull shape factor $k = 2$, the fractional rms wind difference is 6% for an intercomparison producing $R^2 = 0.985$, or 4% for an $R^2 = 0.995$. We have also checked this result via a simulation in which 1000 random mast

winds are generated from a Weibull distribution, and for each mast wind a remote instrument wind is generated with an additional normally distributed variation.

3. CUP-SODAR DIFFERENCES DUE TO TURBULENCE

A cup anemometer measures the total wind run in a sampling period, whereas a remote sensing instrument averages the vector wind components measured during a sampling period. Kristensen [4] has described the bias arising from this different method of measuring wind, as follows.

The wind speed measured by a cup anemometer is

$$U_{m,n} = \sqrt{(U + u_n)^2 + v_n^2} \quad (5)$$

whereas a remote sensing instrument measures the vector

$$\underline{U}_{r,n} = (U + u_n \quad v_n \quad w_n). \quad (6)$$

The average measured by the mast-mounted cup anemometer is (to second order)

$$\begin{aligned} \overline{U_{m,n}} &= \frac{1}{N} \sum_{n=1}^N U_{m,n} \\ &= \frac{U}{N} \sum_{n=1}^N \left(1 + 2 \frac{u_n}{U} + \frac{u_n^2}{U^2} + \frac{v_n^2}{U^2} \right)^{1/2} \\ &\approx U + \frac{1}{N} \sum_{n=1}^N \frac{v_n^2}{2U} \end{aligned} \quad (7)$$

whereas that measured by a remote instrument is

$$\overline{\underline{U}_{r,n}} = \frac{1}{N} \sum_{n=1}^N \underline{U}_{r,n} = (U \quad 0 \quad 0) \quad (8)$$

or speed $\overline{U_{r,n}} = U$. The normalized mean difference between mast and remote measured winds is

$$\frac{\overline{U_{m,n}} - \overline{U_{r,n}}}{U} = 1 + \frac{1}{2} \left(\frac{\sigma_v}{U} \right)^2. \quad (9)$$

The term in brackets is the transverse turbulent intensity and the difference in measured wind speeds will be typically in the range of 0 to 8%.

The work of [4] did not describe the random differences arising from scalar vs vector averaging. For a particular turbulence intensity these two different measures of wind speed will give rise to scatter in a plot of winds

measured by mast instruments versus winds measured by remote instruments. This scatter derives from the variance in the difference $\overline{U_{m,n}} - \overline{U_{r,n}}$. For the cup measurements

$$\sigma_m^2 = \frac{1}{N} \sum_{n=1}^N (U_{m,n} - \overline{U_{m,n}})^2 \approx \sigma_u^2 \quad (10)$$

and for the remote measurements

$$\sigma_r^2 = \frac{1}{N} \sum_{n=1}^N (U + u_n - U)^2 = \sigma_u^2 \quad (11)$$

so the variance of the difference is

$$\Delta U_{rms}^2 = \sigma_m^2 + \sigma_r^2 = 2\sigma_u^2 \quad (12)$$

However, wind measurements are typically averaged over 10 minutes. For a SODAR having a range of 300m, this is typically an average over around 70 wind estimates. The result is a reduction in the variance by about 60, giving

$$\frac{\Delta U_{rms}}{U} \approx \frac{1}{6} \frac{\sigma_u}{U}. \quad (13)$$

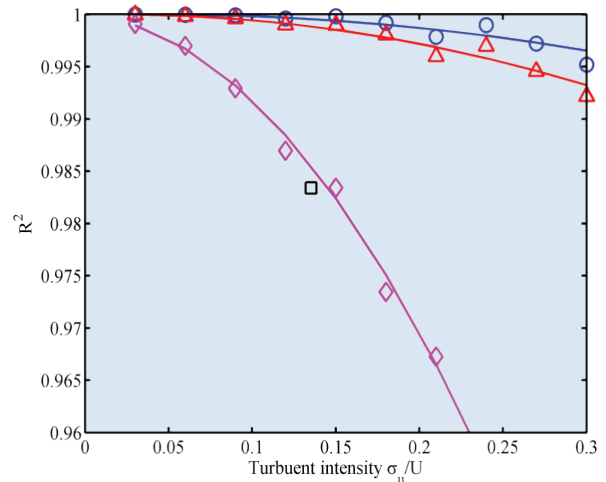


Figure 2. The effect on R^2 of scalar-vector averaging differences (circles), of a mast-SODAR separation of 80m (triangles) and of successively sampling from 3 volumes (diamonds). In all cases the Weibull scale parameter = 8 m s^{-1} , and shape factor = 2. Also shown is a data point from WISE (square).

The normalized standard deviation between mast and remote measured winds is therefore proportional to the turbulence intensity, and the scatter naturally affects R^2 . We can simulate this by generating winds U from random Weibull deviates, and then generating random u_n, v_n, w_n values for a succession of samples at this U . These turbulent components are generated by filtering a

white noise spectrum to obtain a Von Karman velocity spectrum. Fitting a straight line to the resulting scatter plot gives R^2 values for each chosen turbulence intensity, as shown in Fig. 2.

Remote sensing instruments measure the wind vector components in directions x , y , and z by solving (or fitting solutions to) equations which relate the wind components to the Doppler shift along each radial beam direction. As an example, a 3-beam system having two beams tilted at angle θ off-vertical and one vertical beam, would solve equations like

$$\begin{aligned} m_{n,1} &= (U + u_{n,1}) \sin \theta + w_{n,1} \cos \theta \\ m_{n,2} &= v_{n,2} \sin \theta + w_{n,2} \cos \theta \\ m_{n,3} &= w_{n,3} \end{aligned} \quad (14)$$

with solution

$$\begin{aligned} U_{r,n} &= \frac{m_{n,1} - m_{n,3} \cos \theta}{\sin \theta} \\ &= U + u_{n,1} + (w_{n,1} - w_{n,3}) / \tan \theta \end{aligned} \quad (15)$$

In this case

$$\frac{\Delta U_{rms}}{U} = \sqrt{\left(\frac{\sigma_u}{U}\right)^2 + \frac{2}{\tan^2 \theta} \left(\frac{\sigma_w}{U}\right)^2}. \quad (16)$$

The effect of this time delay in sampling distributed volumes is also simulated using the random Von Karman method, and is also shown in Fig. 2. One measured point from the WISE PIE campaign is also shown, as a square: this compares closely with the simulation.

Depending on the site, a SODAR can receive reflections from fixed non-atmospheric objects. This ‘fixed echo’ effect produces a second Doppler spectrum peak centered on zero Doppler shift. If the wind speed is relatively low, then the two spectral peaks can overlap and an incorrect lower estimate of the wind speed is obtained from the composite peak. In fact the same problem occurs with LIDAR systems and stray laser energy, but the effect only occurs for wind speeds below 3 m s^{-1} . In the case of SODARs, a comparable limit occurs, providing the spurious zero-Doppler peak and the required atmospheric reflection peak are of comparable magnitude. Unfortunately, this often is not the case if a SODAR is placed close to a mast. Consequently, SODAR-mast intercomparisons are inevitably conducted with the SODAR placed 80m or more from the mast. This introduces a further difference between the SODAR measured wind and the mast sensor winds, since the same volume of air is not being sensed. The fixed echo problem could be greatly reduced for SODARs if their design was with a greater

off-vertical beam angle θ , such as 30° used by some LIDAR systems instead of the 15° typical of most SODARs. Fig. 2 also shows the effect on R^2 of a mast-SODAR separation of 80 m, using the same turbulence simulation method. In Fig. 2, the three turbulence-related effects are treated separately. It is clear that, even in uniform terrain, the sampling of three or more spatially separated volumes by a SODAR, over a time interval of something like 9 s, is the main cause for reduced R^2 .

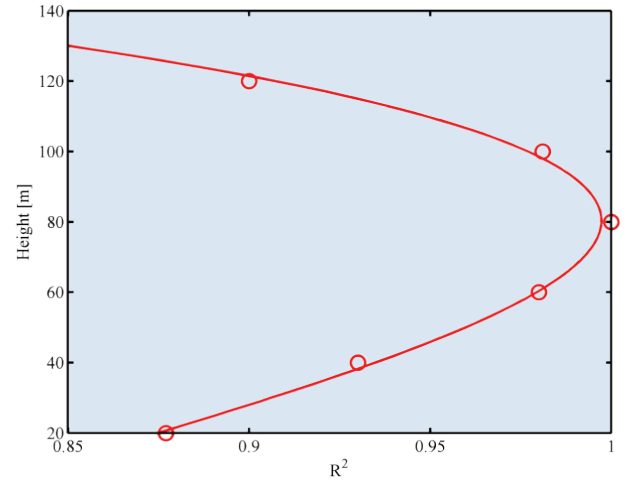


Figure 3. R^2 versus height for opposing beams aligned with the wind (adapted from Behrens et al. [5]). Measurements (circles), theory (solid line).

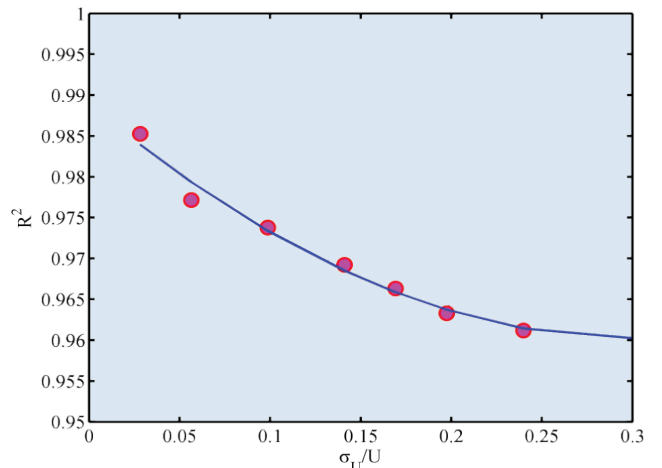


Figure 4. Measured R^2 and σ_u/U values inferred from [5]. The measurements were in complex terrain.

This effect has also been explored experimentally [5]. Fig. 3, adapted from this work, shows the correlation as a function of height between two opposing beams aligned with the wind for a five-beam Metek SODAR. A very high R^2 is measured at the height where turbulence from one sampled volume has moved to the second sampled volume in the time between sampling the two volumes. Measurements in complex terrain of

ΔU_{rms} vs mast measured σ_u are also given in [5]. In Fig. 4 we have assumed reasonable values of \bar{U} and σ_u^2 so as to be able to plot these measurements as R^2 vs σ_u/U . The measured values follow roughly the predictions from Fig. 2.

The general conclusion from the above is that, in uniform terrain under low acoustic background noise conditions and retaining only those measurements during low turbulence, very high R^2 values can be anticipated for SODARs. This approach would match that taken over the past few years in showing that LIDARs can match closely the winds measured by cup anemometers. To date this type of careful intercomparison experiment has not been performed on SODARs. Note that such an intercomparison does not match what might be expected as typical field experience with these instruments. Indeed, it may be necessary to discard entire days of data in order to obtain optimal conditions, unlike with resource surveying or monitoring.

4. SODARS IN COMPLEX TERRAIN

It is now well-established that remote sensing instruments exhibit large errors in wind speed estimation in complex terrain [5][6][7]. There is only one theoretical model for the effect of complex terrain on spatially-separated sampling of wind by remote sensing instruments [7]. This theoretical model is based on potential flow over a bell-shaped hill of height-to-width h/L .

The speed-up of flow over the hill crest means that a mast placed at the top of the hill will measure higher winds than a remote sensing LIDAR or SODAR, since these instruments perform some of their measurements in volumes to the side of the hill peak where the wind speed is lower. In this case remote sensing produces an under-estimation in wind speed. Similarly, an instrument mounted half-way up the hill slope may do some of its measurements in a higher wind speed regime closer to the crest, thereby giving an over-estimation of wind speed. This model is very simple, but performs well when compared with field measurements in complex terrain [8][9]. The model in [7] gives estimates of errors for different hill geometries, different remote sensing configurations and orientations, but a simple approximation can be made. The fractional error in estimating the wind speed for a 3-beam sodar sited on the crest of the hill, with beam 1 facing downwind, is

$$\frac{\Delta U_{rms}}{U} \approx -5G_{max}^2 \frac{z}{H} \quad (17)$$

where z is the height of the sensing volume above the hill crest, H is the hill height, and G_{max} is the maximum gradient of the bell-shaped hill. The fractional error is negative because the maximum speed is directly above the instrument in this case, and the beam directed in the direction of the flow underestimates. So for a hill of maximum gradient 0.1, and with $z = H$, a 5% error in wind estimation is predicted. This is comparable to the error measured in practice in complex terrain, and is unacceptably high for wind energy applications. Note that this error is *generic* across all SODARs and LIDARs, and is insensitive to the beam zenith angle θ . Also, unlike the turbulence-related variations between remote instrument and mast sensor, the complex terrain difference is a systematic error.

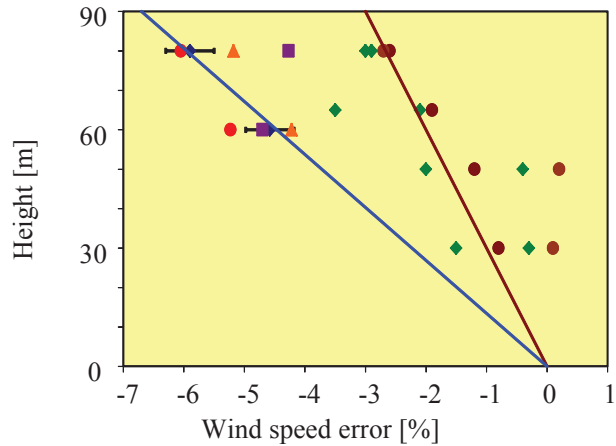


Figure 5. Measurements at a moderate hill site (ZephIR lidar measurements in green, AQ500 sodar measurements in brown), and at a complex site (Metek sodar measurements in blue). Model results are shown for a bell-shaped hill potential-flow model (orange), WindSim (purple) and OpenFOAM (red) for the complex site.

Fig. 5 shows complex terrain errors measured for both a ZephIR LIDAR and an AQ500 SODAR at Myres Hill in Scotland. These errors are characterized by their increasing with height. It can be seen there is no statistical difference between the LIDAR and SODAR errors. Measurements have also been made at Turitea in New Zealand [9], and compared with various flow models, also shown in Fig. 5. Again, similar errors are seen with increasing height. The simple bell hill model compares well with the industry-standard WindSim and the complex CFD OpenFoam model [9].

5. CONCLUSIONS

Given the above discussed differences between mast and SODAR, what is the best current estimate of the fundamental wind speed errors in a SODAR? We have distinguished *differences* and *errors*. Differences (between a SODAR and a mast-mounted cup anemometer) will arise due to turbulent fluctuations and

wind components being measured in different spaces, as well as to variable background noise. Such differences can be minimized by selecting the environment and selectively filtering the data for periods of low fluctuations. The commonly quoted R^2 values for remote sensing instruments are *not* a property of the instrument.

There is real difficulty therefore in answering the question: How good is a SODAR? Most field use, away from the idealized 'lab' environment, seem to have an R^2 value of 0.975 to 0.985. From Eq. (3), this corresponds to a range of relative difference, compared to a cup anemometer, of 6% to 5%. For a 10 m s^{-1} mean wind speed, this corresponds to about 0.5 m s^{-1} rms difference. It is not known how this range compares with LIDARs under similar conditions, although there is some evidence that those institutions who have been operating both a LIDAR and a SODAR together or in similar environments are finding little difference.

We have examined, both analytically and via simulations, how the random differences between SODARs and cups could arise. It appears that the dominant effect is likely to be sampling from three spatially-separated volumes, each of which has different turbulent components. We have, in the current work, only evaluated this effect for one SODAR beam configuration, but the principle should apply for others. We have given supporting experimental evidence, but it would be good to test some of these predictions in a more rigorous field campaign. One approach to reducing this source of variation is to continuously transmit on all beams, instead of waiting for the return time of individual pulses.

All current remote sensing instruments produce winds with errors in complex terrain. The errors become larger for a steeper hill or for measuring further above the ground. These errors can be estimated from flow models, and actual field measurements suggest a relatively simple model (which can be run on a laptop in a few seconds) gives predictions comparable to much more complex models. There appears to still be more work required to demonstrate that the combination of in situ remote sensing measurements and flow models can robustly produce wind data of the required accuracy.

Both the turbulence-related random fluctuations and the complex terrain errors can potentially be removed by use of a vertical column geometry. As noted, this geometry also has other advantages, but it does have the disadvantage of having to distribute three sensors on the ground instead of one. However, a new design in progress has each of the two passive receivers as being quite small and mobile (can be carried in one hand).

Current experience being reported by virtually all SODAR users is very positive, with relatively little or no maintenance time. However, care does need to be taken with regard to nearby trees or other structures to ensure that the wind record is not contaminated by fixed echo returns.

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